Revised regional correlations and tectonic implications of Paleoproterozoic and Mesoproterozoic metasedimentary rocks in northern New Mexico, USA: New findings from detrital zircon studies of the Hondo Group, Vadito Group, and Marqueñas Formation

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ABSTRACT

Detrital zircon ages from quartzite and metaconglomerate in the Tusas and Picuris Mountains in northern New Mexico reveal new information about age and provenance trends within a >1000 km^2 Proterozoic sedimentary basin and provide a critical test of regional correlations. Samples from the Paleoproterozoic Vadito and Hondo groups are dominated by a single detrital zircon population with age probability peaks that range from 1765 to 1704 Ma. Minor Archean and ca. 1850 Ma age probability peaks were also recognized in some samples. Close correspondence between detrital zircon ages and the age of surrounding basement rocks indicates predominately local sources, and we interpret systematic shifts in peak ages with stratigraphic position to represent changes in local sources through time. Similarities of age spectra support previous correlation of stratigraphic units between discontinuous exposures of the Hondo Group. We interpret that these supracrustal rocks were deposited in a single basin that we refer to as the Pilar basin.

Two samples of the Marqueñas Formation, a pebble to boulder conglomerate previously correlated with the ca. 1700 Ma Vadito Group, are dominated by Paleoproterozoic detrital zircon with age probability peaks at 1707 and 1715 Ma in the middle and upper units, respectively. Unlike the Vadito and Hondo group samples, the Marqueñas Formation also contains abundant ca. 1700–1600 Ma zircon derived from Mazatzal-aged sources to the south and Mesoproterozoic zircon with age probability peaks at 1479 and 1457 Ma. Weighted averages of 1477 ± 13 Ma and 1453 ± 10 Ma for the youngest detrital zircon in the middle and upper Marqueñas Formation provide new maximum depositional age constraints, indicating that it is not part of the Vadito Group. The minimum age is not well constrained but is interpreted to be ca. 1435 Ma on the basis of the timing of regional metamorphism and deformation previously documented in the Picuris Mountains. These data represent the first evidence of sedimentation directly associated with ca. 1.4 Ga regional metamorphism, plutonism, and deformation in the southwestern United States and provide an important new constraint on the tectonic evolution of southern Laurentia during this time.

INTRODUCTION

Thick metasedimentary successions that include abundant quartz arenite are exposed throughout the southwestern United States and in many Paleoproterozoic orogens around the world (e.g., Dott, 1983; Rosen et al., 1994; Cox et al., 2002; Medaris et al., 2003; Betts and Giles, 2006; Rainbird and Davis, 2007; Jones et al., 2009). Regional and global correlation of these distinctive sequences provides key piercing points for proposed Proterozoic supercontinent reconstructions (e.g., Dalziel, 1991; Burrett and Berry, 2000; Sears and Price, 2000; Karlstrom et al., 2001; Goodge et al., 2008) and constrains tectonic models for the growth and stabilization of continental lithosphere (Giles et al., 2002; Jones et al., 2009). In the southwestern United States (Fig. 1), quartzite and related rhyolite successions are key marker units for distinguishing the age and tectonic setting of events that resulted in growth of southern Laurentia during the Paleoproterozoic (Karlstrom and Bowring, 1988; Hoffman, 1988; Williams, 1991; Jessup et al., 2006; Whitmeyer and Karlstrom, 2007; Amato et al., 2008; Jones et al., 2009).

Perhaps the single greatest impediment to understanding the tectonic significance of these quartzite successions involves uncertainties about the timing of deposition. Absolute ages are only available for a small number of localities (e.g., Bauer and Williams, 1989; Cox et al., 2002), and the limited geographical extent of individual quartzite exposures complicates the correlation of the successions at the regional and global scale. Cross-cutting relationships observed throughout the southern Rocky Mountains (Fig. 1) indicate that deposition occurred in cycles following regional orogenesis at ca. 1.70 and 1.65 Ga (Amato et al., 2008; Jones et al., 2009). However, the duration of sediment deposition, local and regional basin geometries, and the structural and metamorphic evolution of the successions are not well understood.

Here we present new detrital zircon geochronology for rocks from the Paleoproterozoic Vadito and Hondo groups in northern New Mexico (Bauer and Williams, 1989; Bauer, 1993). The Vadito and Hondo groups consist of >3 km of metasedimentary and metavolcanic rocks that are exposed in multiple mountain ranges over an area greater than 1000 km^2 (Figs. 1 and 2). These rocks are broadly correlated with multiple quartzite successions exposed to

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the north in Colorado (Jones et al., 2009) and to the west in Arizona (Cox et al., 2002), and their outcrop trend suggests that they were deposited in an elongated depositional basin we refer to as the Pilar basin (Fig. 2). We interpret the Pilar basin to represent one of multiple northeast-striking, broadly contemporaneous basins that formed in southern Colorado, northern New Mexico, and central Arizona ca. 1.7 Ga following the culmination of the Yavapai orogeny (Fig. 1; Jones et al., 2009). The correlation of units within the Vadito and Hondo groups was revised and formalized by Bauer and Williams (1989) and is widely accepted in the region. However, provenance studies are only available for a small number of localities, and correlations within the groups are complicated by uncertainty in absolute and relative age constraints and poorly exposed contact relationships. Our new results confirm some of the previous correlations and provide new insight into the provenance of the thick metasedimentary succession. However, our findings also require an important revision to the Proterozoic lithostratigraphy of the region and may also have direct bearing on models for regional metamorphism and deformation during the Mesoproterozoic.

GEOLOGICAL SETTING

Exposures of Precambrian rocks across the southwestern United States show a diverse assemblage of metavolcanic and metasedimentary rocks with plutons that range from mafic to felsic composition. These rocks were formed and accreted to the southern margin of the Archean Wyoming province between 1800 Ma and 1600 Ma (Condie, 1982; Karlstrom and Bowring, 1988; Reed et al., 1993) as part of a protracted period of Laurentian crustal growth (Whitmeyer and Karlstrom, 2007). These exposures have been divided into several orogenic provinces on the basis of rock ages and isotopic

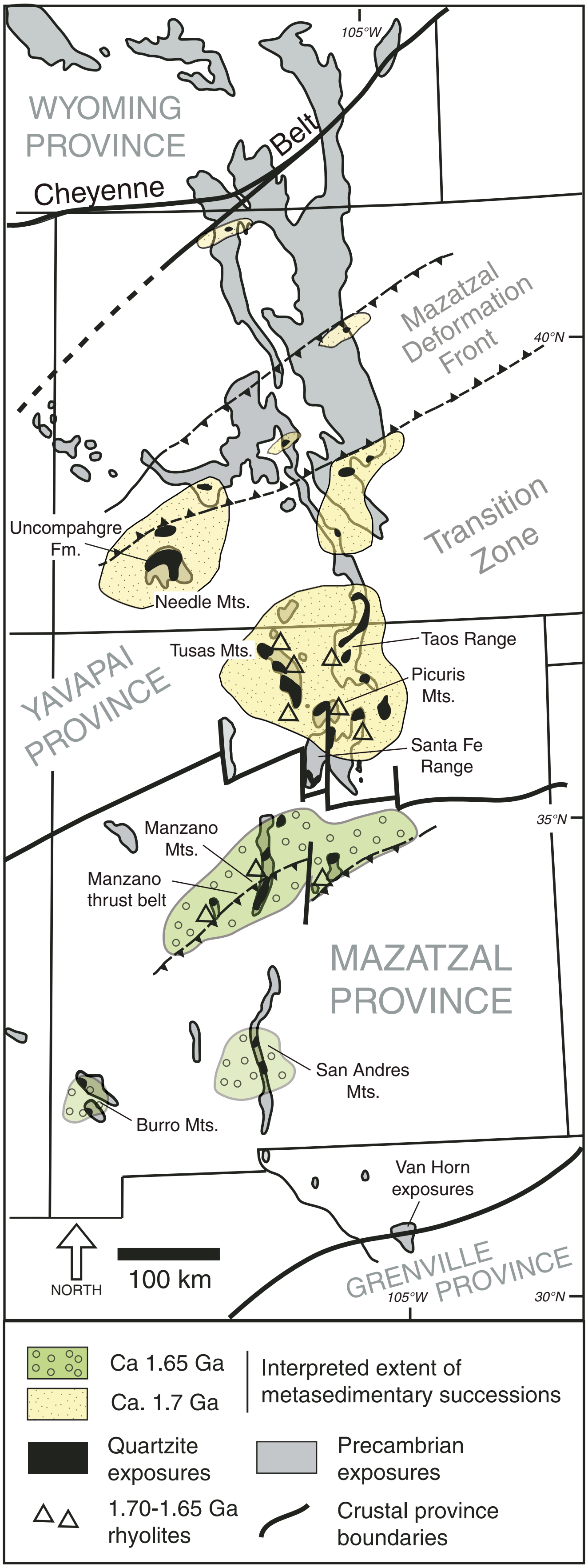


Figure 1. Paleoproterozoic quartzite successions of the southern Rocky Mountains, U.S.A. Outcrop localities mentioned in the text are labeled accordingly. Faults shown without thrust teeth are either inferred thrust faults or strike-slip faults. The outlines of possible Paleoproterozoic depocenters are from Jones et al. (2009) and highlight ca. 1.70 Ga metasedimentary successions that might be broadly correlative. The Pilar basin discussed in the text is at the southern end of the southern Colorado–northern New Mexico depocenter outline and is highlighted in Figure 2.

characteristics (Fig. 1). The Yavapai province is interpreted to represent a complex collage of predominantly juvenile arc terranes characterized by rocks with Nd model ages between 2000 and 1800 Ma (Bennett and DePaolo, 1987). Rocks of the Yavapai province were accreted to the Laurentian margin between 1780 and 1700 Ma along a belt stretching from Colorado to Arizona and New Mexico. The final collisional phase of this long-lived, progressive orogenic event occurred ca. 1710–1700 Ma (Karlstrom and Bowring, 1988), and was followed by voluminous postorogenic granitoid magmatism from ca. 1690 to 1650 Ma (Anderson and Cullers, 1999).

The Mazatzal province lies south of the Yavapai province and extends across central and southern New Mexico and Arizona (Fig. 1).

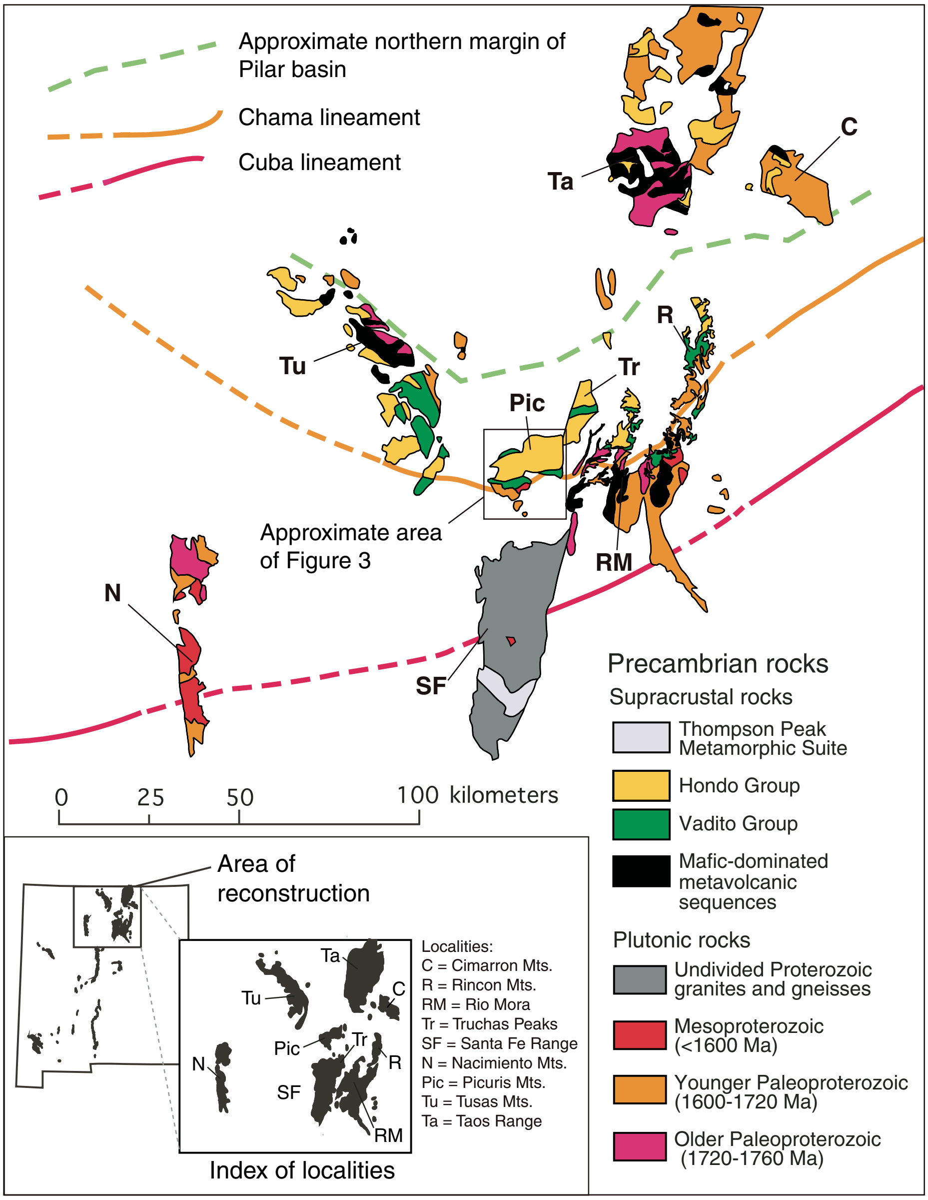


Figure 2. Reconstruction of Proterozoic orogenic belt across north-central New Mexico (after Karlstrom and Daniel, 1993; Cather et al., 2006). Exposures of Hondo and Vadito Group rocks correspond to regional aeromagnetic lows that we interpret to represent the extent of the Pilar basin development. Outcrop localities discussed in text are labeled on the inset and map and reconstruction: C—Cimarron Mountains; N—Nacimiento Mountains; Pic—Picuris Mountains; R—Rincon Mountains; RM—Rio Mora; SF—Santa Fe Range; Ta—Taos Range; Tr—Truchas Peaks; Tu—Tusas Mountains.

Mazatzal province rocks are characterized by Nd model ages between 1800 and 1700 Ma (Bennett and DePaolo, 1987) and were accreted to southern Laurentia during the 1660–1600 Ma Mazatzal orogeny (Silver, 1965; Karlstrom and Bowring, 1988; Luther, 2006; Amato et al., 2008). Mazatzal-aged deformation affected a large foreland region of the southern Yavapai province (Transition Zone, Fig. 1; Karlstrom and Humphreys, 1998), and the Mazatzal Deformation Front represents the approximate northern extent of these effects (Shaw and Karlstrom, 1999). Various workers have challenged the juvenile arc accretion model for the Yavapai and Mazatzal orogenies on the basis of zircon ages, lithological associations, and limited Hf isotopic data (Bickford and Hill, 2007a; Bickford et al., 2008), but alternative models are still being evaluated and debated (Duebendorfer, 2007; Karlstrom et al., 2007; Bickford and Hill, 2007b).

After a ca. 100 m.y. tectonic lull from ca. 1600 to 1500 Ma, renewed southward growth of Laurentia is inferred to have occurred during the Mesoproterozoic. This interpretation is based upon Nd model ages of 1500–1300 Ma from the granite-rhyolite province that extends from northern Mexico to Labrador, Canada (Bennett and DePaolo, 1987; Patchett and Ruiz, 1989; Karlstrom et al., 2001). An episode of widespread granitic magmatism and local emplacement of mafic dikes occurred throughout the southwestern United States between 1470 and 1360 Ma (Williams, 1991; Reed et al., 1993; Williams et al., 1999), and rocks of this age currently account for nearly 20% of all Precambrian exposures across the region. High crustal temperatures of 300–750 °C during the same time caused regional greenschist- to near granulite-facies metamorphism (Grambling et al., 1989; Williams and Karlstrom, 1996; Williams et al., 1999; Daniel and Pyle, 2006) and reset argon ages throughout the region (Grambling and Dallmeyer, 1993; Karlstrom et al., 1997; Shaw et al., 1999, 2005; Sanders et al., 2006). Circa 1.4 Ga granites, previously described as being A-type because of their alkalinity, anhydrous character, and presumed anorogenic tectonic setting (Loiselle and Wones, 1979; Anderson, 1983), are ferroan in nature (Frost et al., 2001), a geochemical characteristic that is indicative of mantle influence (Frost and Frost, 1997) and is generally associated with extensional tectonic environments such as continental rifting (Emslie, 1978; Whalen et al., 1987; Eby, 1990).

However, regional evidence exists for shortening or strike-slip deformation within the thermal aureoles of plutons and contemporaneous reactivation of northeast-striking crustal shear zones in the Rocky Mountains and southwestern United States (Graubard and Mattinson, 1990;

Shaw et al., 2001; McCoy et al. 2005; Jessup et al., 2006; Jones et al., 2010). Kinematic evidence for regional, northwest-directed crustal shortening synchronous with pluton emplacement and regional metamorphism suggests that ca. 1.4 Ga magmatism coincided with regional orogenesis associated with a convergent plate boundary along the distal southern margin of Laurentia (e.g., Nyman et al., 1994). These events were all part of a prolonged, ca. 800 m.y. episode of crustal growth along the long-lived "southern" margin of Laurentia that culminated in the Grenville orogeny and assembly of the supercontinent Rodinia at ca. 1.1 Ga (Karlstrom et al., 2001).

Proterozoic Quartzite Successions

During the southward growth of Laurentia, successions of quartz sandstone up to 2 km thick were deposited within the orogenic belts. Quartzite successions occur in both the Yavapai and Mazatzal provinces, and include extensively exposed units like the Ortega Formation (New Mexico) and Uncompahgre Formation (Colorado) as well as numerous smaller, more localized exposures with similar lithologies and outcrop characteristics (Fig. 1). Existing age constraints suggest that sedimentation occurred ca. 1700–1680 Ma following the Yavapai orogeny (Jones et al., 2009) and ca. 1650–1600 Ma following the Mazatzal orogeny (Luther et al., 2005a, 2006; Luther, 2006; Amato et al., 2008). Quartzite is commonly nearly pure (>95% quartz) with minor muscovite, Al-silicates, hematite, zircon, and monazite. Primary sedimentary structures are locally well preserved, including common cross stratification. Depositional facies are similar from bottom to top and region to region and indicate shallow marine (<10 m water depth) or fluvial environments (Trevena, 1979; Soegaard and Eriksson, 1985, 1989; Harris and Eriksson, 1990).

In many outcrop localities, quartzite directly overlies thick successions of voluminous, high-silica rhyolite (Fig. 1). The contact between rhyolite and quartzite is generally interlayered to gradational and is commonly marked by a distinctive, Mn-rich contact interval (Bauer and Williams, 1989). Basement rock assemblages underlying quartzite-rhyolite successions regionally are typically characterized by metamorphosed mafic volcanic rocks and volcanogenic marine metasedimentary rocks (Bauer and Williams, 1989; Jessup et al., 2005). Examples of these older (1800–1720 Ma; Condie, 1982) assemblages include the Pecos, Gold Hill, and Moppin complexes in northern New Mexico (Bauer and Williams, 1989) and the Dubois and Cochetopa successions in southern Colorado (Bickford and Boardman, 1984). Basement rocks commonly contain evidence for multiple episodes of deformation and/or metamorphism that are not recognized in the overlying quartzite (Gibson and Harris, 1992). Thus, the contact between basement assemblages and quartzite successions has been variably interpreted as an unconformable depositional contact, a sheared unconformity, or a fault contact.

The quartzite-rhyolite successions and underlying basement assemblages were deformed by folding and thrust imbrication. Across Colorado, quartzite exposures are found as tight, upright synclinal "keels" interpreted to be the roots of larger, now eroded folds (Wells et al., 1964; Reuss, 1974; Jones et al., 2009). In the Needle Mountains of southwestern Colorado and Tusas Mountains of northern New Mexico, 1–2-km-thick sections of quartzite define tight to open, large-wavelength (kilometer-scale) folds consistent with some fold-and-thrust-belt geometries (Harris, 1990; Williams, 1991; Williams et al., 1999). Deformation and metamorphism of quartzite successions in the southern Yavapai province are interpreted to have occurred during accretion of the Mazatzal province to the south (Jones et al., 2009). The metasedimentary successions were metamorphosed at greenschist- to amphibolite-facies conditions prior to ca. 1450 Ma, when they were widely intruded by coarse-grained granitic plutons (Barker, 1969; Reuss, 1974; Jessup et al., 2006; Jones and Connelly, 2006). Deformation and metamorphism of Mazatzal province successions possibly occurred during the waning stages of the Mazatzal orogeny (Luther et al., 2005a; Amato et al., 2008) but may have also occurred during the Mesoproterozoic (Baer et al., 2003; Amato et al., 2011).

PROTEROZOIC GEOLOGY OF NORTHERN NEW MEXICO

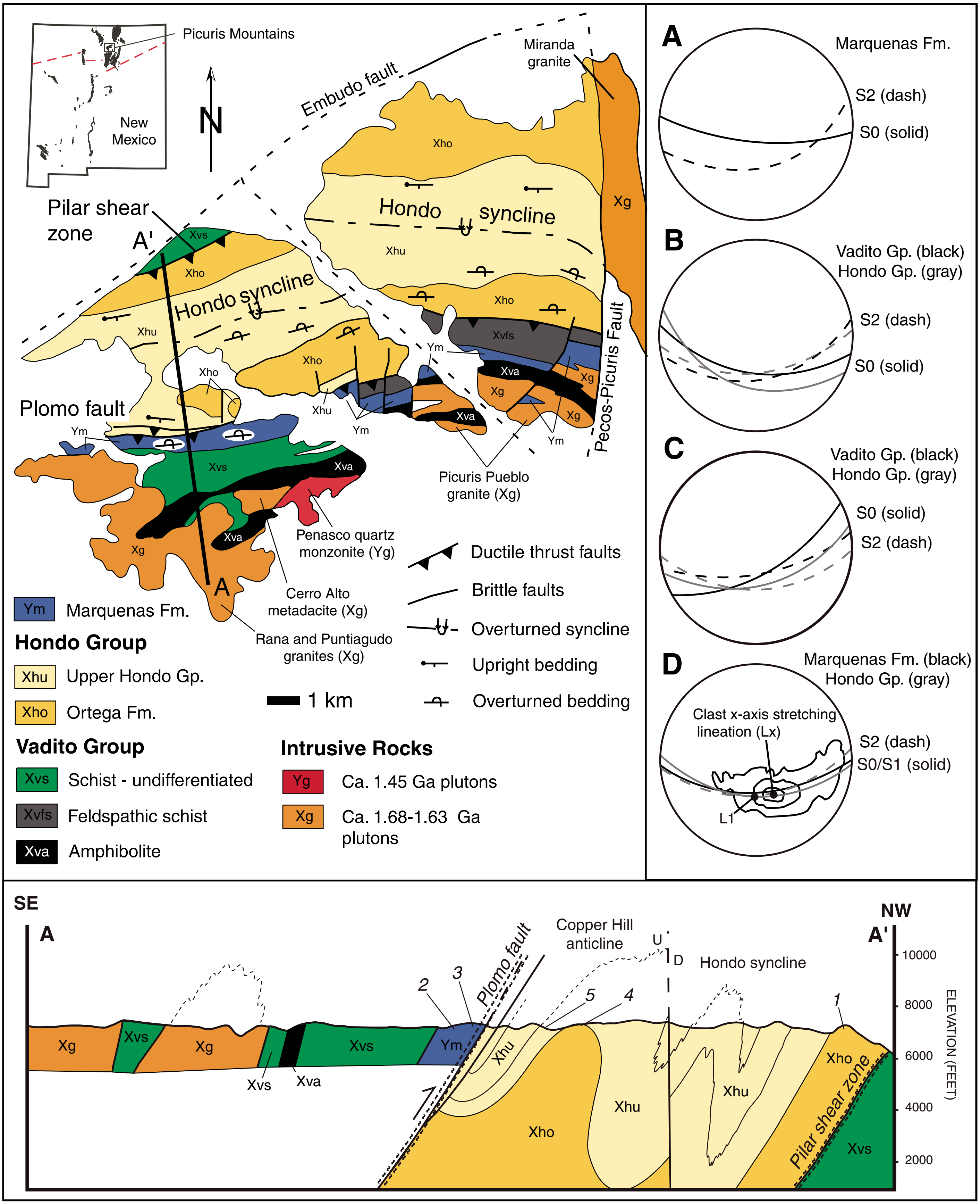
Lithostratigraphy

Exposures of Proterozoic rocks in northern New Mexico are dominated by granite-greenstone associations, supracrustal successions, and granitoids (Karlstrom et al., 2004). The oldest units include the ca. 1770–1750 Ma Moppin and Gold Hill complexes exposed in the Tusas Mountains and Taos Range, respectively (Figs. 1 and 2; Bauer and Williams, 1989, and references therein), and the ca. 1720 Ma Pecos complex, exposed in the eastern Santa Fe Range (Fig. 2). These complexes are dominated by mafic metavolcanic rocks but also include felsic metavolcanic rocks, metasedimentary rocks, and iron formation (Bauer and Williams, 1989; Robertson and Condie, 1989; Karlstrom et al., 2004). They are represented in black in Figure 2, and they are widely intruded by calc-alkaline tonalite to granodiorite plutons (purple in Fig. 2). The Moppin and Gold Hill complexes are interpreted to have been formed in arcs in a marine setting (Condie, 1986). Robertson and Condie (1989) interpreted that the Pecos complex was formed in a backarc setting, possibly in a continental margin setting.

The Vadito and Hondo groups are successions of metavolcanic and metasedimentary rocks that are in unconformable or tectonic contact with the older mafic complexes. These successions are exposed in mountain ranges throughout northern New Mexico and are represented in yellow and green in Figures 2 and 3. Units within the Vadito Group are not well defined across northern New Mexico (Fig. 4; Bauer and Williams, 1989). Stratigraphic relationships are obscured by discontinuous exposure, a seemingly greater degree of stratigraphic variation along strike (Bauer and Williams, 1989), and multiple phases of deformation that disrupted and possibly repeated parts of the original stratigraphy (Fig. 3). In the Picuris Mountains, the lowermost section of the Vadito Group largely consists of amphibolite with minor quartz-biotite-muscovite schist, cross-bedded impure quartzite, and metaconglomerate. To the north, various schist and minor quartzite are dominant. Rare cross stratification within quartzite lenses indicates stratigraphic younging to the north. McCarty (1983) interpreted these rocks as interlayered graywacke, quartzite, volcaniclastic sediment, and basaltic flows, and inferred a deep-water basin setting for deposition.

The 500-m-thick Marqueñas Formation is exposed to the north of schists of the lower Vadito Group in the Picuris Mountains (Figs. 3 and 4B). It consists of a lower, poorly sorted, highly strained, polymictic boulder conglomerate, a middle quartzite, and an upper, highly strained, pebble-to-cobble conglomerate. Cross stratification within the Marqueñas Formation indicates that the layering is overturned and that the unit youngs to the north, supporting stratigraphic interpretations that place the Marqueñas Formation within the Vadito Group (Fig. 4B; Bauer and Williams, 1989). Previous work (Miller et al., 1963; Grambling, 1979; Grambling and Codding, 1982) in the Truchas Peaks and Rio Mora areas (Fig. 2) east of the Picuris Mountains documented a relatively thick sequence of conglomerate that is correlated with the Marqueñas Formation.

The uppermost part of the Vadito Group is represented by the Glenwoody Formation in the Picuris Mountains (Fig. 4B). This unit comprises ~300 m of feldspathic schist that is exposed beneath the Ortega Formation in the northern Picuris Mountains (Bauer and Williams, 1989). Despite poor exposure of the upper and lower



Picuris Mountains
New Mexico
N
Embudo fault
Miranda granite
Pilar shear zone
A'
Hondo syncline
Plomo fault
Pecos-Picuris Fault
Picuris Pueblo granite (Xg)
Penasco quartz monzonite (Yg)
Cerro Alto metadacite (Xg)
Rana and Puntiagudo granites (Xg)
A
Ym Marquenas Fm.
Hondo Group
Xhu Upper Hondo Gp.
Xho Ortega Fm.
Vadito Group
Xvs Schist - undifferentiated
Xvfs Feldspathic schist
Xva Amphibolite
Intrusive Rocks
Yg Ca. 1.45 Ga plutons
Xg Ca. 1.68-1.63 Ga plutons
1 km
Ductile thrust faults
Brittle faults
Overturned syncline
Upright bedding
Overturned bedding
A Marquenas Fm.
S2 (dash)
S0 (solid)
B Vadito Gp. (black)
Hondo Gp. (gray)
S2 (dash)
S0 (solid)
C Vadito Gp. (black)
Hondo Gp. (gray)
S0 (solid)
S2 (dash)
D Marquenas Fm. (black)
Hondo Gp. (gray)
Clast x-axis stretching lineation (Lx)
L1
S2 (dash)
S0/S1 (solid)
SE
NW
A
A'
Copper Hill anticline
Hondo syncline
Plomo fault
Pilar shear zone
U
D
1
2
3
4
5
10000
8000
6000
4000
2000
ELEVATION (FEET)

contact, Bauer and Williams (1989) interpreted the Glenwoody Formation to represent the upper Vadito Group (Fig. 4B) locally on the basis of similarities with other upper Vadito Group rocks in other ranges and the presence of a Mn-rich horizon that is typically found high in the Vadito Group stratigraphy. Bauer et al. (2005) mapped transitional rocks between the Vadito and Hondo groups in the eastern Picuris Mountains. These transitional units are described as feldspathic schists of the Vadito Group that grade laterally into various quartzite, conglomerate, and schistose quartzite and conglomerate units that grade upward into the massive orthoquartzite of the Ortega Formation (Bauer et al., 2005). The stratigraphy here is disrupted by the Plomo fault, but Bauer et al. (2005) suggested that these rocks are equivalent to similar transitional rocks in the Tusas Mountains (Fig. 4).

In the Tusas Mountains to the west (Figs. 1 and 2), Vadito Group exposures are dominated by immature quartzofeldspathic metasedimentary rocks and felsic metavolcanic rocks (Bauer and Williams, 1989). These rocks range from highly schistose to massive and are interlayered with amphibolite, cross-bedded muscovite quartzite, feldspathic quartzite, biotite-muscovite schist, conglomerate, and pelitic schist (Bauer and Williams, 1989, and references therein). The contacts between these different rock types are poorly exposed and are obscured by polyphase deformation that involved isoclinal folding and development of penetrative metamorphic foliations. One notable unit within the Vadito Group stratigraphy in the Tusas Mountains is the ~60-m-thick Big Rock Formation (Fig. 4A). This unit is divided into a lower member dominated by conglomerate with minor interlayered micaceous quartzite and an upper member dominated by micaceous and feldspathic quartzite (Bauer and Williams, 1989). Metaconglomerate layers contain elongate cobbles up to 20 cm in diameter, and the cobble compositions include vein quartz, quartzite, schist, and metarhyolite. The clast size is smaller on average than the Marqueñas Formation, and the Marqueñas Formation metaconglomerate is thicker and is interlayered with a larger volume of impure quartzite. Otherwise, the two units are lithologically similar and display younging criteria such as cross beds and graded bedding suggesting that they are stratigraphically beneath the Hondo Group. Thus, they were tentatively correlated within the upper Vadito Group by Bauer and Williams (1989) and Bauer (1993) (Fig. 4).

The upper Vadito Group in the Tusas Mountains contains the Burned Mountain Formation (Fig. 4A). It is dominated by metarhyolite that contains distinctive quartz and feldspar eyes in a fine-grained, laminated matrix (Bauer and Williams, 1989). The formation ranges in thickness from 4.5 to 30 m and yielded a U-Pb zircon age of ca. 1700 Ma (Bauer and Williams, 1989). This age is interpreted to represent crystallization

Figure 3. Simplified geologic map of the Picuris Mountains and cross section (A–A′) across the western part of the range showing the relationship of the Marqueñas Formation to the Vadito and Hondo groups (modified from Bauer, 1993; Bauer and Helper, 1994). Approximate sample locations of (1) J07-PIC1, (2) J07-PIC2, (3) J07-PIC3, (4) J07-PIC4, and (5) J07-PIC5 are shown in the cross section in the appropriate structural position. Summary stereonet plots for the area surrounding the sampled Marqueñas Formation exposures show (A) average orientation of S0 and S2 in the Marqueñas Formation after McCarty (1983); (B) average orientation of S0 and S2 in the Vadito and Hondo groups after Holcombe and Callendar (1982); (C) average orientation of S0 and S2 in the Vadito and Hondo groups after McCarty (1983); and (D) average orientation of S0/S1 and S2 in the Hondo Group together with the average L1 stretching lineation on S0/S1 in the Hondo Group after Bauer (1988). The contours show the X-axis (stretching lineation) of clasts in the Marqueñas Formation after Nielsen and Scott (1979).

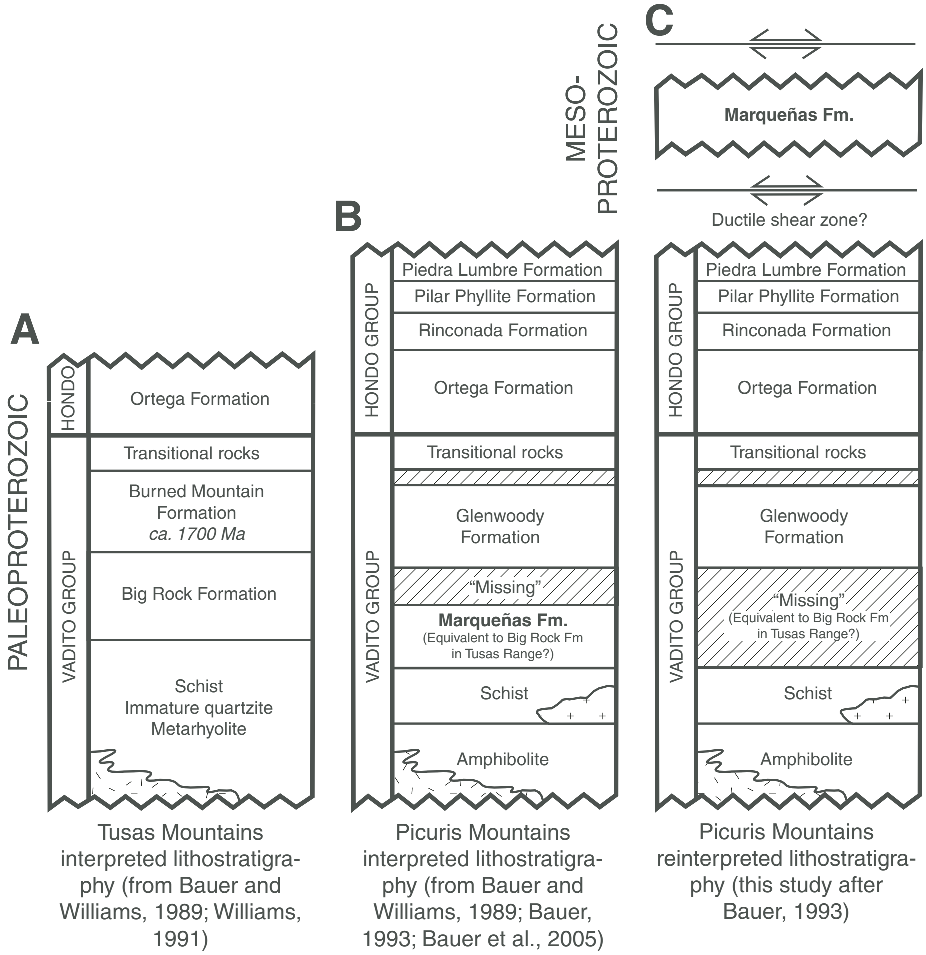


Figure 4. Interpretive structural and stratigraphic reconstructions of Proterozoic lithostratigraphic sequences in the Tusas and Picuris Mountain, New Mexico. (A) Lithostratigraphic relationships of the Vadito and Hondo groups, Tusas Mountains, northern New Mexico (Bauer and Williams, 1989; Williams, 1991). (B) Lithostratigraphy of the Vadito and Hondo groups, Picuris Mountains, northern New Mexico (modified from Bauer, 1993). (C) Reinterpreted lithostratigraphy of (B) showing the Mesoproterozoic Marqueñas Formation in unconformable depositional contact or fault contact with the Paleoproterozoic Vadito and Hondo groups.

of the rhyolitic protolith, thus providing one of the only constraints on the absolute age of the Vadito and Hondo. The uppermost Vadito Group in the Tusas Mountains is characterized by immature micaceous quartzite (Transitional rocks in Fig. 4A) that grades upward into more thickly bedded orthoquartzite of the lower Ortega Formation.

The Hondo Group (Fig. 4) overlies the Vadito Group and consists of several metasedimentary formations. The basal Ortega Formation, an ~1-km-thick, cross-bedded quartzite, is overlain by interlayered pelitic schist and cross-bedded quartzite of the Rinconada Formation. Upsection, the Pilar Formation consists of a black graphitic phyllite followed by graphitic, garnet-biotite schist, phyllite and micaceous quartzite of the Piedra Lumbre Formation. Soegaard and Eriksson (1986) interpreted the Hondo Group to represent fluvial to shallow-marine deposition on a southward-deepening siliciclastic shelf.

Proposed reconstructions of right-slip faulting across the Tusas, Picuris, Truchas, and Rio Mora ranges (Karlstrom and Daniel, 1993; Daniel et al., 1995; Cather et al., 2006) bring Proterozoic rock units and deformational features into alignment and help define an east-west trend of Vadito and Hondo group exposures that we refer to as the Pilar basin (Fig. 2). The Pilar basin sits just north of a pronounced geophysical lineament interpreted to represent a major Proterozoic accretionary boundary in the southwestern United States (Fig. 1; Karlstrom and Humphreys, 1998). A zone of relatively weak magnetism located north of the Chama lineament corresponds well with the surface exposures of the Vadito and Hondo groups (Cather et al., 2006). We interpret this magnetic low to represent the continuation of these groups in the subsurface and, therefore, place the approximate northern boundary of the basin along its northern edge. Quartzite exposures north of this boundary in the Cimarron and Taos ranges may be correlative with the Hondo Group (Fig. 2). Furthermore, the northwestern trend of the Pilar basin in Figure 2 suggests that the Hondo Group might also be correlated with the Uncompahgre Formation in the Needle Mountains of southwestern Colorado (Fig. 1). However, these correlations have not yet been tested, and the quartzite-rhyolite association of the Vadito and Hondo groups has not been recognized in these areas.

Deformation and Metamorphism of the Hondo Group, Vadito Group, and Marqueñas Formation

Three generations of ductile deformation are recognized in exposures of the Hondo Group, Vadito Group, and Marqueñas Formation in northern New Mexico (Williams, 1991; Bauer, 1993; Williams et al., 1999). D1 includes local bedding-parallel foliation (S1) and fold nappes (Williams, 1991; Read et al., 1999). D2 produced the dominant, penetrative foliation (S2), north-verging, km-scale inclined folds (F2) and ductile faults in the Picuris and Tusas Mountains (Nielsen and Scott, 1979; Holcombe and Callender, 1982; McCarty, 1983; Bauer, 1988, 1993; Williams, 1991). D3 structures include weakly developed upright, open folds and an associated crenulation cleavage (S3), but the distribution and intensity of D3 deformation is heterogeneous throughout the region (Williams et al., 1999). Deformation was accompanied by multiple metamorphic events (M1–M3), culminating with regional amphibolite-facies metamorphism to 550–700 °C ca. 1.47–1.42 Ga (Williams et al., 1999). Map relationships around dated plutons and textural studies of dated minerals indicate that D3 deformation occurred ca. 1.42 Ga (Read et al., 1999; Williams et al., 1999; Daniel and Pyle, 2006). The ages of D1 and D2 deformation are more uncertain and could be ca. 1.65 or 1.42 Ga (Williams et al., 1999; Daniel and Pyle, 2006). Williams (1991) and Bauer (1993) proposed that D2 represents a progressive north-vergent deformational event that could possibly be a continuation of a more cryptic D1 regional deformation.

In the Picuris Mountains, relict bedding (S0) in the Marqueñas Formation strikes east and dips steeply south (Fig. 3A; McCarty, 1983), roughly parallel to S0 in Vadito and Hondo Group rocks to the north and south (Figs. 3B and 3C; Holcombe and Callender, 1982; McCarty, 1983). Consistent stratigraphic-facing direction throughout the Marqueñas Formation indicates that the unit is overturned to the north but is not internally folded. The Marqueñas Formation does not contain the same bedding-parallel schistosity (S1) that is observed in schistose units of the Vadito Group, so it is possible that the Vadito and Hondo Groups were deformed and metamorphosed at least once prior to F2 folding. But the Marqueñas Formation does contain an east-northeast–striking, steeply south-dipping penetrative tectonic foliation that is similar in style and orientation to the dominant, penetrative S2 foliation in Vadito and Hondo Group rocks (Figs. 3A–3C; Bauer, 1988, 1993). The Plomo fault is a steeply south-dipping zone of high strain that separates the Marqueñas Formation from folded Hondo Group rocks to the north (Bauer, 1993). Quartzite clasts in the Marqueñas Formation are strongly flattened in a mylonitic foliation that parallels the fault contact, and elongated clasts define a prominent south-plunging stretching lineation (Fig. 3D) with reverse-sense (top-up-to-the-north) kinematics (Bauer, 1993). These relationships suggest that, at a minimum, the Marqueñas Formation was deformed together with the Vadito and Hondo groups during megascopic F2 folding and ductile shearing along the Plomo fault in the Picuris Mountains. The shear zone cuts across the S2 foliation and north-vergent F2 folds (Fig. 3; Bauer, 1993; Bauer and Helper, 1994), indicating that some ductile movement on the fault postdated D2. The total stratigraphic separation across the Plomo fault is not well established but is estimated to be as much as several kilometers (Bauer, 1993).

Metamorphic mineral assemblages in exposures throughout the Picuris Mountains indicate amphibolite-facies conditions during the dominant D2 deformation, and the Marqueñas Formation locally contains garnet, biotite, and chlorite in thin, schistose partings. Peak metamorphic conditions throughout the range were near the aluminosilicate triple point (500–550 °C, and 4.0 kb; Holdaway, 1978; McCarty, 1983; Grambling and Williams, 1985; Read et al., 1999; Williams et al., 1999; Daniel and Pyle, 2006) at or near the time of major folding (Nielsen and Scott, 1979; McCarty, 1983; Bauer, 1988, 1993). Kyanite and sillimanite are typically deformed and are thus interpreted to be pre- to syntectonic with respect to F2 folding and shearing (Bauer, 1988, 1993). Andalusite crystallized after most of the folding, indicating that metamorphism outlasted deformation in the Picuris Mountains and surrounding ranges (Grambling and Williams, 1985; Grambling et al., 1989; Bauer, 1993; Williams, 1991; Bauer, 1993). Subhorizontal metamorphic isograds appear to overprint map-scale ductile structures (Grambling, 1979; Grambling and Williams, 1985; Bauer, 1993). In exposures of Vadito Group schists ~50–100 m south of the Plomo fault and the Marqueñas Formation, Williams et al. (1999) reported metamorphic conditions of 600–650 °C and 3 kb for andalusite- and cordierite-bearing rocks. Monazite inclusions within andalusite porphyroblasts were reported to be ca. 1450 Ma (Williams et al., 1999). In Hondo Group rocks exposed in the northern Picuris Mountains, Daniel and Pyle (2006) documented peak metamorphic conditions of 525–540 °C and 4.0–4.2 kb that occurred between 1450 and 1435 Ma. The disparity in pressures and temperatures from south to north may reflect late movement across the Plomo fault. Alternatively, the pressure gradient may reflect a difference in erosion level, with greater uplift and erosion along the northern margin of the Picuris Mountains relative to the south, possibly related to uplift along the Embudo fault zone. Temperature differences between the northern and southern Picuris Mountains may partly reflect differences

in the petrogenetic grids used to estimate temperatures. Williams et al. (1999) used Pattison's (1992) triple point, ~550 °C and 4.5 kbar, versus the triple point of Holdaway (1971), ~500 °C and 4 kbar, used by Daniel and Pyle (2006).

DETRITAL ZIRCON GEOCHRONOLOGY

Methods

We present new U-Pb detrital zircon age data for quartzite and conglomerate collected from exposures in the Tusas Mountains and Picuris Mountains in northern New Mexico. Sample processing followed the methodology of Jones and Connelly (2006). Following an initial magnetic separation to remove paramagnetic minerals and zircon with abundant inclusions, the remaining zircon grains were handpicked to include populations representing each of the various morphologies, sizes, and colors that were recognized. Approximately 150 grains from each sample were mounted in 1-inch epoxy discs and ground and lightly polished to reveal the grain surfaces. We analyzed zircon at the Geological Survey of Denmark and Greenland (GEUS) using single-collector, laser ablation–magnetic sector field–inductively coupled plasma–mass spectrometry (LA-SF-ICP-MS) techniques described by Frei and Gerdes (2009).

Age data are summarized in Table 1, and full analytical data and sample location coordinates are available in Supplemental Table 1[1]. Figures 5 and 6 show age-distribution curves and U-Pb concordia diagrams for all detrital zircon from all samples. Figure 7 shows age-distribution curves of ≤10% discordant Proterozoic detrital zircon for all samples together with published detrital zircon data from Ortega Formation quartzite exposed in the Tusas Mountains, New Mexico (Fig. 7E; Jones et al., 2009) and zircon crystallization ages of basement rocks in central and northern New Mexico (Fig. 7I; Karlstrom et al., 2004). Peak ages in Figures 5–7 represent the weighted average of clusters of three grains or more with overlapping ages (Table 1).

We used Kolmogorov-Smirnoff (K-S) statistics (Press et al., 1986) to help assess the similarity of the detrital zircon age populations among the samples (Berry et al., 2001; Degraaff-Surpless et al., 2003; Dickinson and Gehrels, 2009). We also included published detrital zircon data from other Proterozoic quartzite exposed in New Mexico in the statistical analysis to evaluate possible correlations throughout the broader region. Ortega Formation quartzite exposed in the Tusas Mountains (ORT-N; Jones et al., 2009) was deposited ca. 1690–1670 Ma and derived from >1700 Ma rocks in northern New Mexico and southern Colorado (Jones et al., 2009). Quartzite exposed in the Manzano Mountains (K05-ABO-1Q; Luther, 2006) and San Andres Mountains (SAHC-1Q; Amato et al., 2008) was deposited ca. 1650–1600 Ma and contains abundant <1700 Ma detrital zircon derived from sources in northern and central New Mexico. Results of the K-S test are presented in Table 2. The test mathematically compares two age distributions to determine if there is a statistically significant difference between the two and returns the probability (P) that the two age distributions were drawn from the same population. The P value must be >0.05 to be 95% confident that two populations are not statistically different. The higher the P value, the more likely it is that the two age distributions were drawn from the same population.

Results

In general, the detrital zircon morphologies were remarkably similar among all samples and are dominated by subhedral, subrounded to rounded, and equant to slightly elongate or prismatic grains. A few notable exceptions are described below. Age data summarized in Table 1 indicate that most of the detrital zircon grains analyzed were Proterozoic, with a single dominant age peak between 1800 and 1700 Ma (Fig. 7). Among all samples, the percentage of Archean grains recognized was only 0.9%–7.4%. Analytical results described below are grouped by stratigraphic association and are presented in order of previously interpreted stratigraphic succession.

Big Rock Formation and Marqueñas Formation

We collected quartzite and conglomerate from the middle and upper portion of the Big Rock and Marqueñas Formations to test the proposed correlation of the two units between the Tusas and Picuris Mountains. In the Tusas Mountains, cross-bedded quartzite from the middle of the Big Rock Formation (J07-BR4q) was collected in the hinge zone of the Big Rock syncline (Aby et al., 2010). This sample contained the greatest abundance of euhedral, prismatic grains with only ~5% subrounded to rounded grains. Detrital zircon $^{207}Pb/^{206}Pb$ ages ranged from 2726 to 1674 Ma, and the age-distribution plot contains a single broad peak with a maximum at 1704 Ma together with a small peak at 1840 Ma (Fig. 7H). A cluster of three grains also defines a small peak at 2666 Ma (Fig. 5G; Table 1). Cross-bedded micaceous quartzite from the upper Big Rock Formation (J07-BR5) was collected along the southeast limb of the Posos anticline (Aby et al., 2010). Detrital zircon $^{207}Pb/^{206}Pb$ ages from this sample range from 3322 to 1665 Ma, and the age distribution plot has only a single broad peak with a mode of 1720 Ma (Fig. 7G).

In the Picuris Mountains, we collected two samples of the Marqueñas Formation along Cerro de las Marqueñas between New Mexico State Highway 75 to the south and the Plomo fault and Copper Hill anticline to the north (Fig. 3 cross section). Quartzite from the middle part of the unit (J07-PIC2) yielded detrital zircon with $^{207}Pb/^{206}Pb$ ages ranging from 2900 to 1465 Ma, and the age-distribution curve shows dominant and subsidiary age peaks at 1707 and 1870 Ma, respectively (Fig. 7B). Quartz-pebble conglomerate from the upper part of the unit (J07-PIC3) yielded a detrital zircon $^{207}Pb/^{206}Pb$ age range of 2946 to 1420 Ma (Table 1) with a single dominant age peak at 1715 Ma (Fig. 7A). However, unlike any of the other units collected as part of this study, the youngest age peaks in both of the Marqueñas Formation samples were Mesoproterozoic with ages of 1479 Ma in the middle quartzite (Fig. 7B) and 1457 Ma in the upper conglomerate (Fig. 7A). The Mesoproterozoic peaks are defined by six out of 222 grains in the middle quartzite (2.7%, Table 1) and 21 out of 199 grains in the upper conglomerate (10.6%, Table 1).

The Paleoproterozoic portions of the age-distribution spectra for the Big Rock and Marqueñas Formations overlap with relatively minor variation among the peak ages. The main differences between the four curves are the broadness of the two Big Rock Formation peaks compared to the relatively narrow Marqueñas Formation. The dominant peaks in the Marqueñas Formation samples also skew toward slightly younger ages, indicating a greater abundance of <1700 Ma grains. Results of the statistical tests shown in Table 2 indicate that the two units of the Marqueñas Formation are significantly similar with a P value of 0.357. However, only the Upper Marqueñas Formation is similar to both units of the Big Rock Formation (P values of 0.100 and 0.179). The Middle Marqueñas Formation is statistically similar to the Middle Big Rock Formation (P = 0.242) but not the upper part of the unit (P = 0.034).

The discovery of ca. 1479–1459 Ma zircon in the two Marqueñas Formation samples was the most surprising result of this study. We collected backscattered electron (BSE) images

[1]Supplemental Table 1. Excel file of LA-ICP-MS U-Pb isotopic data and ages. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00614.S1 or the full-text article on www.gsapubs.org to view Supplemental Table 1.

TABLE 1. DETRITAL ZIRCON AGE SUMMARY

Sample	All data: N_{total}	All data: Age range (Ma)	All data: Peak age range(s) (Ma) Minimum	All data: Peak age range(s) (Ma) Maximum	All data: N_{range}	All data: Age peak(s) (Ma)	All data: N_{peak}	90%–110% concordant data: N_{total}	90%–110% concordant data: Age range (Ma)	90%–110% concordant data: Peak age range(s) (Ma) Minimum	90%–110% concordant data: Peak age range(s) (Ma) Maximum	90%–110% concordant data: N_{range}	90%–110% concordant data: Age peak(s) (Ma)	90%–110% concordant data: N_{peak}
Upper Marqueñas Formation conglomerate, Cerro de las Marqueñas, Picuris Mountains														
J07-PIC3	211	1420–2946	1356	1552	26	1456	24	199	1420–2946	1368	1537	23	1457	21
			1575	1929	169	1715	107			1577	1929	162	1715	102
			2050	2068	0					2050	2068	0		
			2099	2106	0					2099	2106	0		
			2360	2364	0									
Middle Marqueñas Formation micaceous quartzite, Cerro de las Marqueñas, Picuris Mountains														
J07-PIC2	229	1465–2900	1439	1514	5	1479	6	222	1465–2900	1439	1514	5	1479	6
			1550	1938	216	1707	140			1569	1938	208	1707	134
			2695	2714	0	1870	11			2695	2714	0	1870	11
Upper Rinconada Formation quartzite, Hondo Group, Copper Hill anticline, Picuris Mountains														
J07-PIC5	108	1686–2892	1609	1947	98	1763	83	102	1686–2892	1609	1938	92	1762	77
			2543	2683	5	2592	5			2543	2683	5	2592	5
Upper Ortega Formation quartzite, Hondo Group, Copper Hill anticline, Picuris Mountains														
J07-PIC4	107	1538–2658	1578	2017	103	1719	69	81	1538–2658	1578	1898	77	1729	55
			2092	2101	1	1763	67						1765	51
						2094	3							
Middle Ortega Formation quartzite, Hondo Group, Tusas Mountains (Jones et al., 2009)														
ORT-N	99	1688–2771	1586	1953	97	1730	93	94	1698–2771	1586	1950	93	1730	90
Middle Ortega Formation quartzite, Hondo Group, Hondo syncline, Picuris Mountains														
J07-PIC1	115	1670–2686	1638	1832	103	1722	93	100	1670–2686	1638	1832	91	1724	83
			1892	1963	3	1935	3			1899	1902	0	2483	3
			2464	2516	3	2490	4			2464	2497	2		
Upper Big Rock Formation micaceous quartzite, Vadito Group, Posos anticline, Tusas Mountains														
J07-BR5	113	1665–3322	1606	1936	106	1720	65	105	1665–3322	1606	1936	98	1720	62
Middle Big Rock Formation quartzite, Vadito Group, Big Rock syncline, Tusas Mountains														
J07-BR4q	113	1674–2726	1630	1883	103	1705	73	102	1674–2726	1630	1883	93	1704	66
			1892	1910	0	1839	7			1892	1910	0	1840	7
			2631	2716	3	2666	3			2631	2716	3	2666	3

Note: N_{total} refers to total number of grains included in age pick analysis. Age range is the total range of ages of all grains included in the age pick analysis. Peak age range represents the range of age-probability contributions (at 2-sigma) from three or more analyses. N_{range} indicates number of ages that contributed to the peak age range. Age peaks represent maxima in the age probability curve comprising three analyses or more. N_{peak} indicates the number of analyses that contribute age probability to an age peak. Age pick data were calculated using Microsoft Excel macros made available by G. Gehrels at the University of Arizona Laserchron Center (Gehrels, 2009).

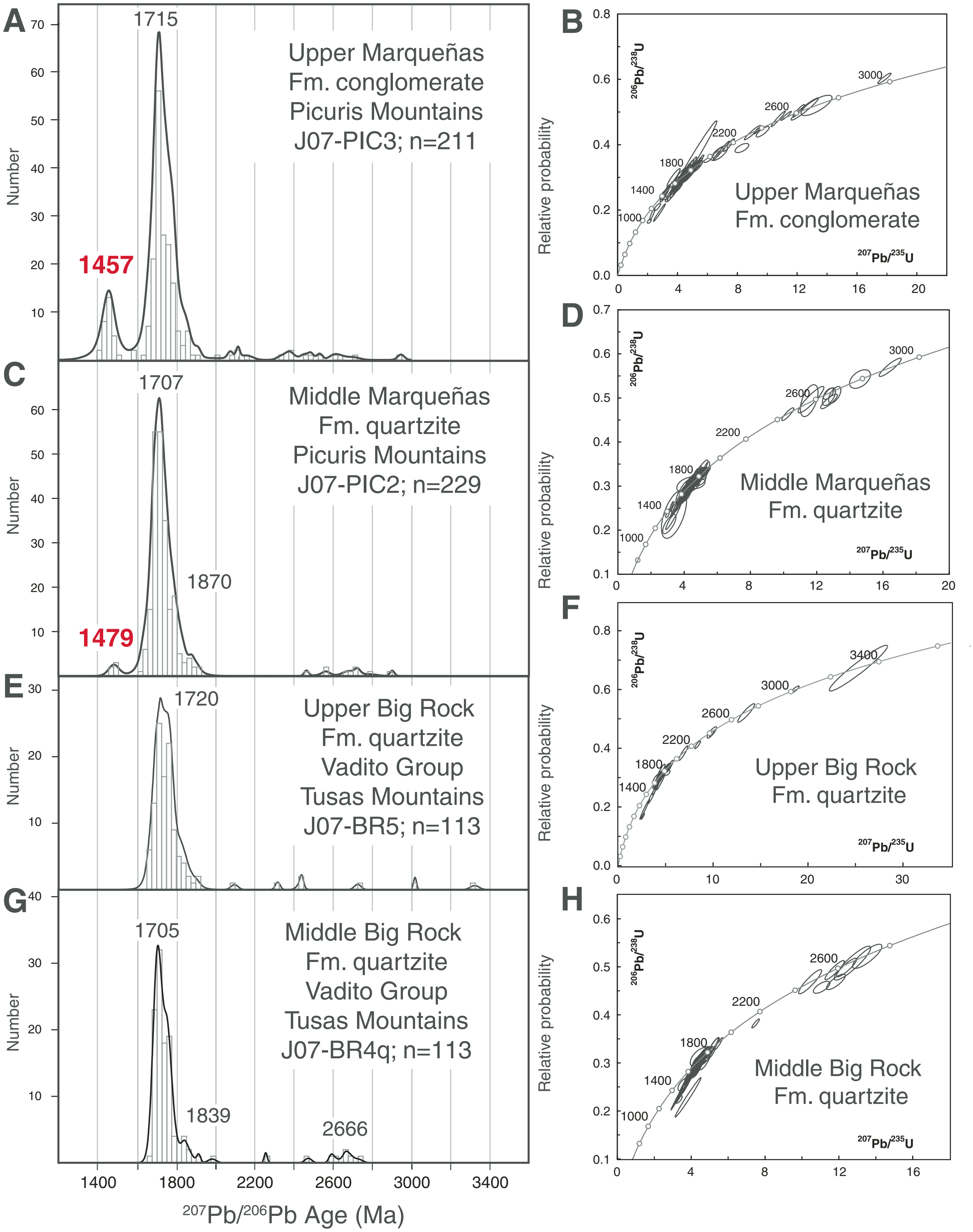


Figure 5. Age-distribution diagrams for ^{207}Pb/^{206}Pb ages and U-Pb concordia diagrams for detrital zircon from the Marqueñas and Big Rock formations, Picuris and Tusas Mountains, New Mexico. Plots represent all grains analyzed, and ages of significant peaks are indicated (Ma, Table 1). Histogram bins are 25 m.y. wide. See Table 1 for a summary of age data and Supplemental Table 1 (see footnote 1) for complete data set.

of the Mesoproterozoic grains to determine if the young ages were the result of metamorphic overgrowths, but most of the grains had well-developed concentric growth zones and no noticeable overgrowths or other internal irregularities (Fig. 8). The other grains did not produce any recognizable internal patterns. The subhedral external morphology of the ca. 1450 Ma grains was consistent with other detrital zircon grains from the same sample and from nearly all of the other samples analyzed during this study. The grains do not match the external morphology of typical metamorphic zircon shown in Corfu et al. (2003). The Th/U ratios of the ca. 1450 Ma grains were among the lowest measured for the two samples with a range of 1.24–0.24 (Supplemental Table 1 [see footnote 1]), but they are not significantly different from the rest of the population or other samples and do not match the very low ratios that are typical for metamorphic zircon (<0.07; Rubatto, 2002). When data acquisition for the two Marqueñas Formation samples was initially completed in 2009, we reanalyzed a subset of the ca. 1450 Ma grains in the upper conglomerate to confirm the original age determinations. In all but one case, both ages were identical within analytical uncertainty (Figs. 8A–8C). In the other case, the second analysis produced an Archean age, suggesting that the grain had an inherited component in its core. Only one ca. 1470 Ma detrital zircon grain was initially recognized in the middle Marqueñas Formation sample. We picked and remounted a new set of zircon samples from the two Marqueñas Formation samples that were analyzed in 2010 using the same techniques, and, again, both samples yielded ages <1500 Ma. The proportion of ca. 1470–1450 Ma grains was ~10% of the total in both data sets for the upper conglomerate (Supplemental Table 1 [see footnote 1]), and the second set of analyses yielded a statistically significant population of ca. 1470 Ma grains in the middle quartzite (four out of 115 analyzed; Supplemental Table 1 [see footnote 1]).

Ortega Formation

We collected two samples from the Ortega Formation in the Picuris Mountains to test the correlation with exposures in the Tusas Mountains and to evaluate possible changes in detrital zircon populations along strike and vertically

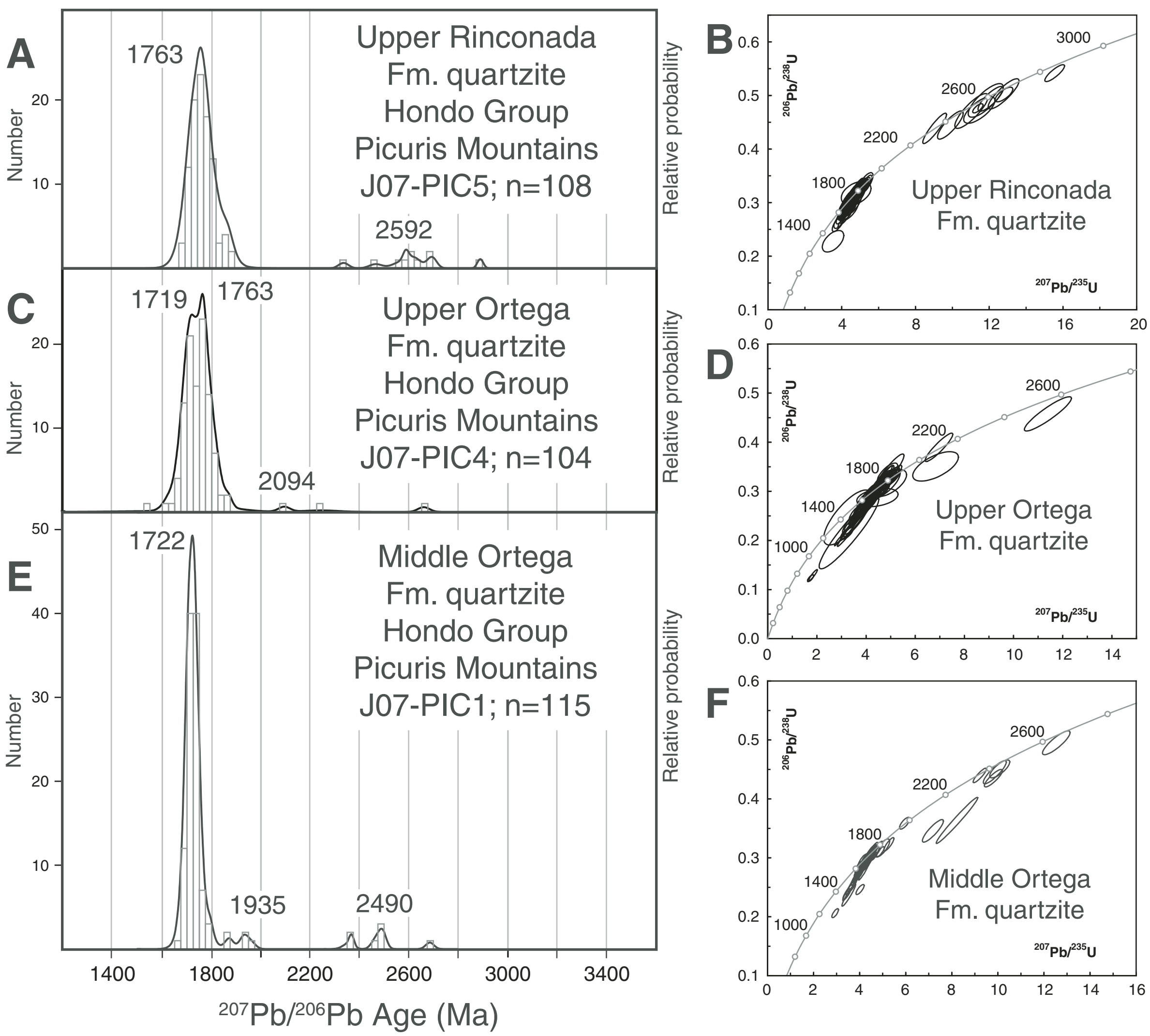
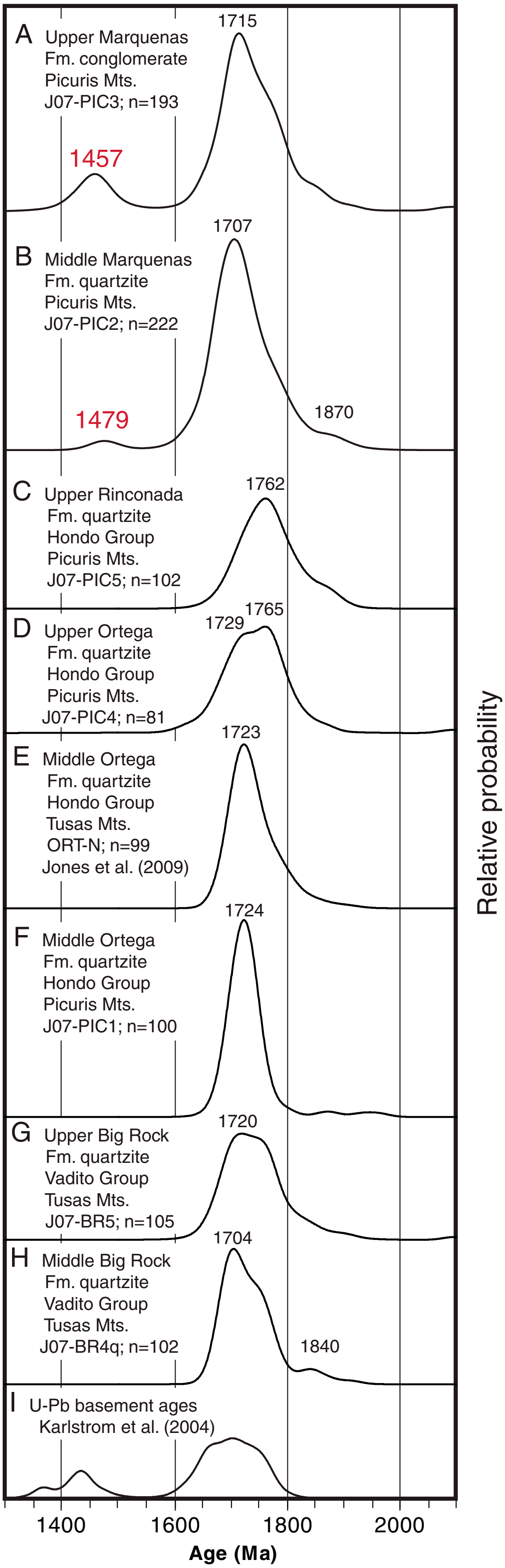


Figure 6. Age-distribution diagrams for ^{207}Pb/^{206}Pb ages and U-Pb concordia diagrams for detrital zircon from the Ortega and Rinconada formations of the Hondo Group, Picuris Mountains, New Mexico. Plots represent all grains analyzed, and ages of significant peaks are indicated (Ma, Table 1). Histogram bins are 25 m.y. wide. See Table 1 for a summary of age data and Supplemental Table 1 (see footnote 1) for complete analytical data.



within the stratigraphic succession. One sample of Ortega Formation quartzite (J07-PIC1), collected from exposures in the northern limb of the Hondo Syncline (Fig. 3), yielded detrital zircon with $^{207}Pb/^{206}Pb$ ages ranging from 2686 to 1670 Ma. The dominant age peak was 1724 Ma (Fig. 7F). Three grains define a separate small age peak at 2483 Ma (Fig. 6E; Table 1). Quartzite from the uppermost part of the unit (J07-PIC4) was collected in the core of the Copper Hill anticline (Fig. 3 cross section), and it yielded detrital zircon with $^{207}Pb/^{206}Pb$ ages of 2658–1538 Ma (Table 1). The age spectrum shows a single broad peak with maxima at 1729 and 1765 Ma (Fig. 7D).

The age-distribution curve and peak age for detrital zircon from the middle Ortega Formation in both the Picuris and Tusas Mountains are nearly identical (Figs. 7E and 7F). The statistical test also indicates that these two samples are significantly similar with a relatively high P value of 0.425 (Table 2). The middle Ortega Formation in the Picuris Mountains is also statistically similar with the middle Big Rock Formation (P = 0.523), but $P<0.05$ when compared with all other samples (Table 2). The upper Ortega Formation is significantly similar with the upper Marqueñas Formation (P = 0.351) and all three samples of Ortega and Big Rock Formation from the Tusas Mountains (P = 0.999–0.596), with a P value of nearly 1 when

Figure 7. Summary of detrital zircon $^{207}Pb/^{206}Pb$ ages (≤10% discordant, Proterozoic grains) and basement U-Pb crystallization ages in Proterozoic exposures in north-central New Mexico. Relative probability diagrams for: (A) conglomerate of the upper Marqueñas Formation, Picuris Mountains; (B) quartzite of the middle Marqueñas Formation, Picuris Mountains; (C) quartzite of the upper Rinconada Formation, Picuris Mountains; (D) quartzite of the upper Ortega Formation, Picuris Mountains; (E) quartzite of the middle Ortega Formation, Tusas Mountains, previously published by Jones et al. (2009); (F) quartzite of the middle Ortega Formation, Picuris Mountains; (G) quartzite of the upper Big Rock Formation, Tusas Mountains; (H) quartzite of the middle Big Fork Formation, Tusas Mountains; (I) basement U-Pb crystallization ages for exposures in northern and central New Mexico (Karlstrom et al., 2004, and references therein). Ages of significant peaks are indicated (Ma, Table 1). Curves are normalized so that area underneath each is the same (Gehrels, 2009).

TABLE 2. DETRITAL ZIRCON AGE SPECTRA COMPARISON USING OVERLAP, SIMILARITY, AND K-S STATISTICS

	J07-PIC3	J07-PIC2	J07-PIC5	J07-PIC4	ORT-N	J07-PIC1	J07-BR5	J07-BR4Q	K05-ABO-1Q
Overlap									
J07-PIC2	0.722								
J07-PIC5	0.728	0.787							
J07-PIC4	0.847	0.593	0.610						
ORT-N	0.448	0.644	0.586	0.452					
J07-PIC1	0.595	0.642	0.794	0.555	0.677				
J07-BR5	0.626	0.600	0.648	0.584	0.557	0.653			
J07-BR4q	0.545	0.693	0.709	0.465	0.774	0.707	0.546		
K05-ABO-1Q	0.599	0.738	0.818	0.558	0.646	0.706	0.577	0.696	
SAHC-1Q	0.362	0.483	0.509	0.424	0.588	0.551	0.416	0.530	0.643
Similarity									
	J07-PIC3	J07-PIC2	J07-PIC5	J07-PIC4	ORT-N	J07-PIC1	J07-BR5	J07-BR4Q	K05-ABO-1Q
J07-PIC2	0.897								
J07-PIC5	0.833	0.842							
J07-PIC4	0.892	0.903	0.885						
ORT-N	0.838	0.882	0.870	0.907					
J07-PIC1	0.820	0.855	0.793	0.840	0.893				
J07-BR5	0.862	0.891	0.868	0.916	0.903	0.857			
J07-BR4q	0.842	0.897	0.863	0.888	0.915	0.885	0.887		
K05-ABO-1Q	0.819	0.908	0.756	0.858	0.805	0.804	0.838	0.841	
SAHC-1Q	0.774	0.872	0.678	0.824	0.754	0.753	0.801	0.781	0.928
K-S statistic									
	J07-PIC3	J07-PIC2	J07-PIC5	J07-PIC4	ORT-N	J07-PIC1	J07-BR5	J07-BR4Q	K05-ABO-1Q
J07-PIC2	0.357								
J07-PIC5	0.000	0.000							
J07-PIC4	0.351	0.019	0.039						
ORT-N	0.038	0.009	0.000	0.668					
J07-PIC1	0.030	0.014	0.000	0.012	0.425				
J07-BR5	0.179	0.034	0.017	0.999	0.890	0.031			
J07-BR4Q	0.100	0.242	0.000	0.596	0.756	0.523	0.835		
K05-ABO-1Q	0.004	0.054	0.000	0.000	0.000	0.000	0.000	0.001	
SAHC-1Q	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.624

Note: Overlap numbers indicate the degree of overlap of two age probabilities where 1.0 is perfect overlap and 0.0 is no overlap. Similarity numbers are a measure of similarity in the proportion of overlapping ages where higher values up to 1.0 reflect similar proportions of overlapping ages and lower values down to 0.0 reflect different proportions of ages that may or may not overlap. K-S statistic numbers indicate the probability (P) that two samples are derived from the same population. The higher the value, the more likely it is that the two age distributions were drawn from the same population. The P value must exceed 0.05 to be 95% confident that the two populations are not statistically different, and those values exceeding 0.05 are shown in bold and shaded in gray. Statistics were calculated using Microsoft Excel macros made available by G. Gehrels at the University of Arizona Laserchron Center (Gehrels, 2009). Samples ORT-N (Jones et al., 2009), K05-ABO-1Q (Luther, 2006), and SAHC-1Q (Amato et al., 2008) are Paleoproterozoic quartzites exposed in the Tusas Mountains, Manzano Mountains, and San Andres Mountains, respectively, and are included for comparison and discussed in the accompanying text.

compared with the upper Big Rock Formation. However, $P<0.05$ when compared with all other samples (Table 2).

Rinconada Formation

We collected one sample (J07-PIC5) from the upper quartzite (Bauer and Helper, 1994) of the Rinconada Formation (Hr5) exposed on the south limb of the Copper Hill anticline (Fig. 3 cross section) to evaluate possible changes in the detrital zircon population vertically within the Hondo Group stratigraphic succession and to provide a baseline for correlation of Rinconada Formation units in exposures throughout the surrounding region (Fig. 2). This sample contained the greatest abundance of rounded to subrounded, equant zircon and few, if any, elongate grains. Detrital zircon $^{207}Pb/^{206}Pb$ ages ranged from 2892 to 1686 Ma (Table 1), and the age-distribution curve is dominated by a single peak with a maximum age of 1762 Ma (Fig. 7C). A cluster of five Archean grains also defines a small peak at 2592 Ma (Fig. 6A; Table 1).

The age-distribution curve for the Upper Rinconada Formation is notably different from the other samples in that it lacks a peak at 1729–1704 Ma and skews toward slightly older ages. The age distribution is most similar to the Upper Ortega Formation and both Big Rock Formation samples because all three have a ca. 1760 Ma component. However, the Upper Rinconada Formation is not statistically similar with any of the other samples included in this study. Comparison with two samples, upper Ortega Formation and upper Big Rock Formation, produces P values of 0.039 and 0.017, respectively, whereas comparison with all other samples returns values of zero (Table 2).

DISCUSSION

Provenance Trends of the Vadito and Hondo Groups

Our results indicate that the detrital zircon populations are very similar among all samples of the Vadito and Hondo groups. We interpret the relatively small number of Archean grains to represent detrital zircon derived from the Wyoming Province to the north (Chamberlain et al., 2003; Jones et al., 2009), but they might represent reworked Paleoproterozoic sedimentary rocks (Hill and Bickford, 2001; Premo et al., 2007). The 1876–1840 Ma peaks that are apparent in only three samples might represent zircon derived from the Trans-Hudson orogen or Black Hills to the north (Van Schmus et al., 1987; Redden et al., 1990) or from the Grand Canyon region or Mojave region to the west (Wooden et al., 1988; Wooden and DeWitt, 1991; Hawkins et al., 1996; Shufeldt et al., 2010). Otherwise, the dominant peaks on the age-distribution curves overlap with zircon crystallization ages of basement exposures from throughout the surrounding region (Fig. 7I). Older peak ages of ca. 1765–1730 Ma represent zircons that were derived from plutonic complexes or greenstone associations such as the Pecos, Moppin, or Gold Hill successions in northern New Mexico (Fig. 2; Karlstrom et al., 2004, and references therein). Younger peak ages of ca. 1730–1704 Ma were likely derived from volcano-plutonic successions that are exposed throughout southern Colorado and northern New Mexico (e.g., Bickford et al., 1989). We interpret these

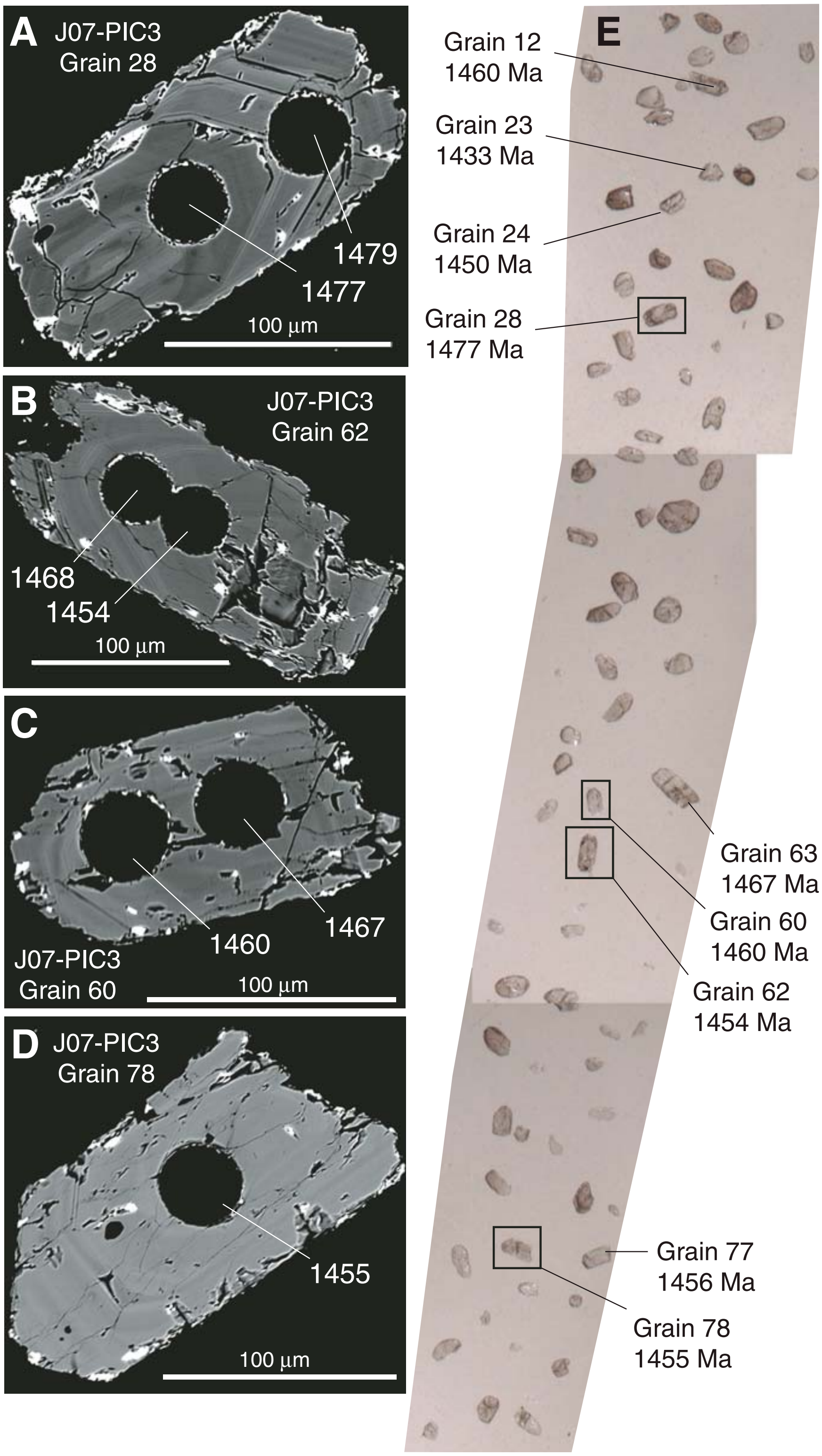


Figure 8. Backscattered electron (BSE) images (A–D) for selected ca. 1470–1450 Ma grains from the upper Marqueñas Formation conglomerate showing laser ablation pits and associated ages (Ma). The photo mosaic on the right (E) shows a representative portion of the grain mount for sample J07-PIC3 that contains multiple <1500 Ma grains. All grain numbers represent the analysis number and are indexed to the data presented in Supplemental Table 1 (see footnote 1).

relationships to indicate predominately local sources for all of the units, with variations in age distributions and age peaks corresponding to the age of the underlying basement. Our findings are consistent with Pb isotopic data of McLennan et al. (1995) and limited detrital zircon data from the Ortega Formation reported by Aleinikoff et al. (1993). Our findings also expand the detrital zircon data set presented by Jones et al. (2009) for ca. 1.70 Ga metasedimentary successions formed in the southern Yavapai Province and support that model for relatively short-lived basins that were dominated by locally derived Paleoproterozoic sediment.

Similarities in the detrital zircon age spectra for samples from the Tusas Mountains are consistent with local evidence for a gradational depositional contact between the Vadito and Hondo groups (Bauer and Williams, 1989). The age ranges and peak ages are similar among the three samples, though the peak in the age-distribution curve is narrower upsection in the Ortega Formation quartzite than in the Big Rock Formation below (Fig. 7). This trend might be the result of changing local source rocks, with highly variable initial sources giving way to more homogeneous sources as the depositional systems evolved. The change might also reflect contrasting depositional environments, with the thick pebble to boulder conglomerate of the Big Rock Formation indicating high-energy fluvial systems and the massive quartzite of the Ortega Formation representing a shallow marine environment (Soegaard and Eriksson, 1985). The age-distribution curves for middle Ortega Formation quartzite are nearly identical between the Tusas and Picuris Mountains, supporting the correlation of Hondo Group rocks between the two ranges. The shift in peak ages toward ca. 1760 Ma in the upper Ortega and Rinconada Formations indicates another change in source rocks toward the end of Ortega Formation deposition.

Age and Provenance of the Marqueñas Formation

Depositional Age Constraints

We interpret the results described above to indicate that the two samples from the Marqueñas Formation have ca. 1479–1457 Ma detrital zircon, a finding that has never been reported among presumed Paleoproterozoic metasedimentary rocks throughout the region. The $^{207}Pb/^{206}Pb$ ages of the five youngest grains from the middle quartzite range from 1489 to 1465 Ma, with a weighted mean of 1477 ± 13 Ma. The $^{207}Pb/^{206}Pb$ ages of 23 grains from the upper conglomerate range from 1481 to 1420 Ma, with a weighted mean of 1453 ± 10 Ma. These ages are interpreted as the best

estimates for the maximum depositional age of the middle and upper Marqueñas Formation, respectively. These new ages indicate that the Marqueñas Formation is not correlative with the ca. 1700 Ma Vadito Group, and our reinterpreted stratigraphic relationships are shown in Figure 4C. The northern contact of the Marqueñas Formation is the Plomo fault, a well-defined ductile shear zone. The southern margin is not well exposed but must represent an unconformity, fault, or both. It is possible that other rocks included within the Vadito Group are associated with the younger Marqueñas Formation as well; however, more work is needed to test this possibility. The minimum depositional age of the Marqueñas Formation is not constrained directly by cross-cutting relationships. The Picuris Pueblo granite exposed in the southeastern Picuris Mountains (Bauer et al., 2005) does appear to intrude eastern exposures of the Marqueñas Formation (Fig. 3) and may provide an independent age constraint on deposition, but it has not yet been dated.

The best available constraints on the depositional age of the Marqueñas Formation come from previous detailed structural and metamorphic studies of the Picuris and adjacent mountain ranges that are described above. All studies of the Picuris Mountains conclude that the Marqueñas Formation experienced the same regional-scale F2 folding event as adjacent rocks of the Vadito and Hondo groups (Miller et al. 1963; Nielsen and Scott, 1979; Holcombe and Callender, 1982; Mawer et al. 1990; Bauer, 1993; Williams et al. 1999). Furthermore, there is abundant evidence that F2 folding was broadly contemporaneous with amphibolite-facies metamorphism involving the growth of all three aluminosilicate minerals, and metamorphic minerals are locally present in aluminum-rich layers of the Marqueñas Formation. Thus, the metamorphic ages described above provide a reasonable lower age constraint on the Marqueñas Formation and suggest that the unit was deposited, deformed, and metamorphosed during the interval between ca. 1453 and 1435 Ma.

Provenance of the Marqueñas Formation

A ca. 1453 Ma or younger depositional age means that the Marqueñas Formation could be derived from the Vadito and Hondo groups, consistent with the interpretations of Soegaard and Eriksson (1986). However, Bauer and Williams (1989) and Mawer et al. (1990) pointed out the disparity of aluminum silicate minerals in Marqueñas Formation cobbles relative to Ortega Formation quartzite and argued that the Ortega Formation was not a likely source for the quartzite clasts. Derivation of detrital zircon from the Vadito and Hondo groups would help to explain the strong similarity of detrital zircon populations between the upper Marqueñas Formation and all other samples except for the upper Rinconada Formation. However, both Marqueñas Formation samples have abundant <1700 Ma zircon (Fig. 7; Table 1) that are not present in the Vadito or Hondo Group. We interpret these ages to represent ca. 1700–1650 Ma volcano-plutonic successions that dominate Proterozoic exposures in northern and central New Mexico and include multiple granitic plutons that intrude the Vadito Group in the southern Picuris Mountains (Figs. 2 and 3; Karlstrom et al., 2004, and references therein).

Similar detrital zircon ages are reported for ca. 1650–1600 Ma quartzites exposed to the south in the Manzano and San Andres Mountains (Luther, 2006; Amato et al., 2008), and the K-S test confirms the similarity of detrital zircon populations among these exposures ($P = 0.624$; Table 2) and between the middle Marqueñas Formation and Manzano Mountains exposures ($P = 0.054$; Table 2). The dissimilarity between the upper Marqueñas Formation and Manzano Mountains quartzite ($P = 0.004$) could indicate a shift to more local or northern >1700 Ma sources upsection, an interpretation that is supported by the slightly older peak age in the upper conglomerate and more pronounced asymmetry on the right-hand (i.e., older) side of the dominant age peak (Fig. 7A).

The range of Mesoproterozoic ages in the two Marqueñas Formation samples corresponds well with the ages of granitoids that intruded throughout the region 1470–1360 Ma (Fig. 7I; Reed et al., 1993; Karlstrom et al., 2004) and overlaps with widespread 1480–1380 Ma rhyolites in the subsurface of the midcontinent to the east (Van Schmus and Bickford, 1981). The 1479 and 1457 Ma age peaks for the middle and upper Marqueñas Formation overlap the upper end of the age spectrum for Mesoproterozoic igneous rocks but predate the ca. 1440–1430 Ma magmatic peak in the Rocky Mountains and southwestern United States (Reed et al., 1993; Karlstrom et al., 2004).

Regional Tectonic Implications

The discovery of Mesoproterozoic detrital zircon in the presumed Paleoproterozoic Marqueñas Formation is significant in a regional tectonic context because it requires that D2 deformation in northern New Mexico occurred ca. 1.43 Ga rather than ca. 1.65 Ga as previously interpreted. We contend that the Marqueñas Formation represents the first known occurrence of pre- to synorogenic metasedimentary rocks associated with ca. 1.4 Ga intracontinental orogenesis in the southwestern United States. The Marqueñas Formation is truncated to the west along the Plomo fault but may be equivalent to conglomerate exposed along strike to the east for ~60 km in the Rio Mora region (Grambling and Codding, 1982). These patterns suggest that deposition could have been locally controlled by movement along the Plomo fault or a precursor structure. The Marqueñas Formation was likely deposited unconformably on Vadito Group exposures, thus explaining the apparent stratigraphic succession south of the Plomo fault (Bauer, 1993). Alternatively, the Marqueñas Formation was faulted against the Vadito Group prior to both rock units being folded and faulted against the Hondo Group. Either interpretation requires significant deformation of the Marqueñas Formation after deposition and provides additional evidence that much of the deformation and metamorphism observed in the Picuris Mountains occurred ca. 1.4 Ga. Furthermore, our findings provide a new line of evidence in the case for ca. 1.4 Ga regional orogenesis in the southern Rocky Mountains within a convergent or transpressional tectonic setting (Nyman et al., 1994; Kirby et al., 1995; Selverstone et al., 2000; Shaw et al., 2001; Jessup et al., 2005; Jones et al., 2010).

We envision a scenario in which the boulder conglomerate and associated quartzite were deposited in a broad alluvial fan that formed in response to a growing orogenic highland to the south. These highlands may be associated with ca. 1.4 Ga movement along the north-vergent Manzano thrust belt (Rogers, 2001; Baer et al., 2003), a series of northeast-striking, north-vergent thrust faults and ductile shear zones exposed in central New Mexico (Fig. 1; Karlstrom et al., 2004; Cather et al., 2006). Uplift of the Manzano Group, a thick succession of volcanic and sedimentary rocks (Luther et al., 2005b; Luther, 2006), along the thrust belt provided ample sources of Paleoproterozoic detrital zircon as well as abundant quartzite and rhyolite clasts. Alternatively, the Marqueñas Formation was derived from more local sources such as the Pecos greenstone, lower Vadito Group, or the many ca. 1670–1620 Ma and ca. 1450 Ma granites exposed in the surrounding region (Fig. 2; Karlstrom et al., 2004). In this scenario, the Marqueñas Formation would be analogous to younger Mesoproterozoic successions such as the Hazel Formation, an orogenic clastic wedge deposited ca. 1120–1080 Ma during the Grenville orogeny in the Van Horn area of western Texas (Fig. 1; Soegaard and Callahan, 1994; Mosher, 1998; Bickford et al., 2000). The Hazel Formation is made up of 2500 m of immature boulder conglomerate and fine-grained sandstone that were derived from a southern tectonic highland and deposited in large, coalescing

alluvial fans immediately north of the frontal zone of the orogen (Soegaard and Callahan, 1994). Age constraints indicate that the boulder conglomerate was deposited within a ca. 50 m.y. time window prior to deformation, a time frame that is similar to the constraints for the Marqueñas Formation described above.

CONCLUSIONS

Detrital zircon geochronology provides a critical test of correlations of Proterozoic metasedimentary rocks exposed within the >1000 km^2 Pilar basin in northern New Mexico and yields new insight into their sedimentary provenance. Our results support previous correlations of quartzite of the Hondo Group between the Tusas and Picuris Mountains and indicate that they were predominately derived from local Paleoproterozoic sources. Systematic shifts in the peak ages of the detrital zircon population within the Hondo Group are interpreted to represent changing source terranes, but the overall age range of the dominant detrital zircon population closely matches the crystallization ages of basement units in the surrounding region. Our results also require a revision of the Proterozoic lithostratigraphy of northern New Mexico. Boulder conglomerate and quartzite of the Marqueñas Formation were previously correlated with the 1700 Ma Vadito Group, but detrital zircon ages require that it was deposited after 1453 Ma. We interpret the Marqueñas Formation to represent a synorogenic succession that was derived from the south and deposited ca. 1450–1435 Ma contemporaneous with regional deformation, metamorphism, and magmatism in the southern Rocky Mountains. Deformation and metamorphism of the Marqueñas Formation involved juxtaposition against poly-deformed, amphibolite-facies rocks of the Hondo Group along the ductile Plomo fault and must have occurred shortly after deposition. This finding represents a new line of evidence in support of regional arguments for orogenesis at ca. 1.4 Ga in a convergent or transpressional tectonic setting.

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